Energetics Study of Mechanically Coupled Human Walking

Honors Undergraduate Thesis

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By

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Abstract

For many decades, researchers have been studying human locomotion in an attempt to completely understand how humans move and why they move in a particular way. Such research has suggested that humans move in a manner that minimizes energy consumption while satisfying other constraints such as stability. To test whether energy optimality is a broadly applicable theory to describe human movement in every situation, human locomotion has been studied in many unique scenarios. Here, we study the energetics of walking in the following unique scenario: when two humans are mechanically coupled together in order to simulate a quadruped. With relatively little research on the energetic effects of different stepping patterns in quadrupeds, the mechanically coupled human scenario allows for a quick, inexpensive way to study this variable. We explored the affects that walking in different stepping patterns has on the total energy consumption of the simulated quadruped. Human subjects walked in various stepping patterns while the ground reaction forces from their legs were recorded. Using the ground reaction forces, we estimated the net mechanical work by the legs, from which we estimated the total metabolic rate of the subjects. The metabolic rate estimate showed that a 90° phase shift was the optimal stepping pattern. However, due to limitations in the mechanical work calculation, this trend may be based on an underestimate of the metabolic rate at these intermediate phases. The preferred stepping pattern of the subjects, estimated using the total time spent in each of the stepping patterns, showed that In-Sync walking was the preferred stepping pattern of the subjects in this mechanically

coupled situation. Further metabolic estimation studies involving oxygen consumption measurements will allow us to more accurately quantify the relationship between metabolic rate and stepping pattern of the simulated quadruped.

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Field of Study

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Chapter 1: Introduction

Section 1.1 Background of energy optimization theory

For many decades, researchers have been studying human locomotion in an attempt to completely understand how humans move and why they move in a particular way (Alexander, 1992). In hopes to find a complete theory to describe human movement in every situation, many unique scenarios have been studied in order to record various human behaviors (Handford and Srinivasan, 2014; Seethapathi, 2015). Through a better understanding of human movement, human behavior in future novel situations, for instance, locomotion on a low gravity planet (Ackerman and van den Bogert, 2012) or on a shaky bridge (Joshi and Srinivasan, 2015) can be envisioned and predicted. Better understanding of human locomotion may lead to better feedback control systems for both robots and human-assistive devices. Unique situations within human movement allow a researcher to study several different concepts through one experiment; such is the case with this project. Here, we analyze human locomotion while two humans are mechanically coupled together, an unnatural and unpracticed situation not faced by humans on a daily basis. Through this coupling of humans, the energetic effects of various stepping patterns can be examined while also analyzing the natural tendencies of the humans in this arrangement. This unique scenario will allow us to test the broad applicability of the hypothesis that humans and animals walk and run in a manner that minimizes energy consumption.

The optimization of energy consumption is a constantly evolving problem that applies to almost every powered system in the world today. How can the energy consumption of the device be reduced so that it is more efficient and can last even longer? Human locomotion appears to be innately energy efficient, say, compared to contemporary robots. Over the years, both experiments and computer models have suggested the energy optimization hypothesis that humans and other animals naturally move in a way that minimizes their energy consumption (e.g., Hoyt and Taylor, 1981; Srinivasan, 2006; Srinivasan and Ruina, 2006; Handford and Srinivasan, 2014). I briefly comment on some of these studies here. One study explored the energetic optimality of humans in both walking and running gaits (Srinivasan, 2006). This paper explored the question as to why humans choose to walk or run when they have an infinite number of different movement types to choose from. The study concluded that the gaits of walking and running are chosen because at those different speeds they are the most energy optimal gaits for the human, adding to the hypothesis of energy optimization. Another interesting result shows that skipping has a higher energy cost than running, providing a reason as to why skipping is not a common preferred gait amongst humans.

Walking and running are not the only gaits where the energy optimization hypothesis has been tested. Research has even been done on unnatural human gaits. One of these unnatural movements is walking sideways. Human subjects, when asked to walk sideways with no prior training, walked within 2.4% of their metabolically optimal speed (Handford and Srinivasan, 2014). The study also showed the metabolic cost for sideways walking to be larger than walking. We can see from this study that when placed in an unusual situation, humans are still very good at moving in a way that is energy optimal. Also, humans naturally avoid more costly gaits such as sideways walking for more energy optimal gaits such as basic walking. Additional studies have been completed that also support many of these presented findings (Zarrugh et al., 1974; Srinivasan and Ruina, 2006). Humans are not the only ones to have been subjects to the testing of the energy optimization hypothesis. Horses have also been shown to naturally move in an energy optimal way (Hoyt and Taylor, 1981).

Hoyt and Taylor (1981) trained horses to walk, trot or gallop (three different types of horse gaits) on a treadmill at a range of speeds. Once familiar with the different gaits and speeds, the horses were put through a series of trials where they moved in these different gaits at multiple speeds while a VO2 oxygen consumption measurement was taken. Afterward, the horses were allowed to naturally move around in an open area and the researchers recorded the speeds with which the horses moved for each particular gait. Figure 1 depicts the collected data from these experiments. In Figure 1, we see three curves showing the data points collected for each type of gait. Each curve has a minimum value corresponding to the energy optimal walking speed for that gait. The bar graph on the bottom of the figure shows how many times the horses were recorded naturally moving at each of the different speeds. As predicted by the study, the horses most often naturally moved at the speeds very close to these energy optimal speeds. The study further strengthens the argument for the energy optimization hypothesis by showing animals other than humans also move in such a way as to optimize their energy consumption.

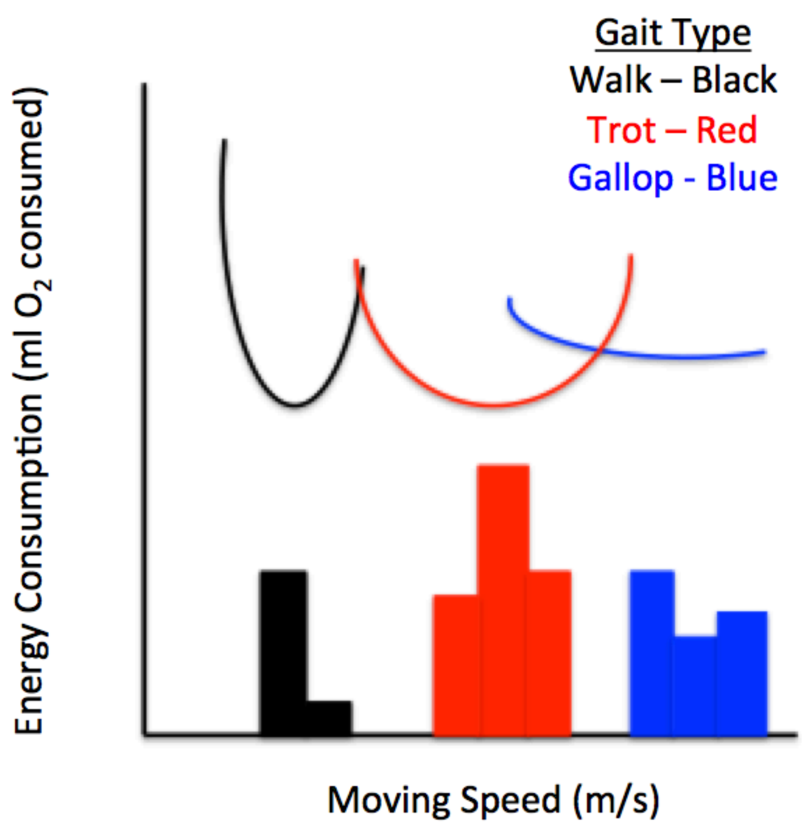

Figure 1. Gait and energetics of locomotion in horses (schematic redrawn from Hoyt and Taylor, 1981).

Section 1.2 Motivation for mechanically coupled human scenario

Along with the mounting evidence for the energy optimization hypothesis, researchers continue to look for innovative situations to explore in order to further strengthen the hypothesis' claim. Through the studies discussed above, many different factors have been shown to affect the total energy expenditure of horses and humans. Walking speed and the gait used for locomotion were shown to have an effect on energy expenditure in humans (Srinivasan, 2006). Stride length is another variable shown to have an energetic significance (Cavanagh and Williams, 1982). Stepping pattern, the motion of individual legs in relation to the other legs, is another energy-effecting variable (Hildebrand, 1989) that is relatively unexplored. Hildebrand's study discusses how different animals move with different "regularly repeating manner(s) of moving the feet," or stepping pattern, and how these movements relate to their energy expenditure. However, the paper does not quantify the effects of stepping pattern in any of the animals. The effect that walking with different stepping patterns has on the total metabolic consumption of a quadruped is a main objective of this research study.

In order to study stepping pattern, a quadruped must be used to obtain the different gaits we want to study. Animals are not easily accessible to most and it is unclear if they can be trained to walk in the unnatural stepping patterns we seek. Therefore, in order to study this variable, a human simulation of a quadruped was created. By mechanically coupling two humans together, as shown below in Figure 2, a quadruped can be simulated and stepping pattern can be explored.

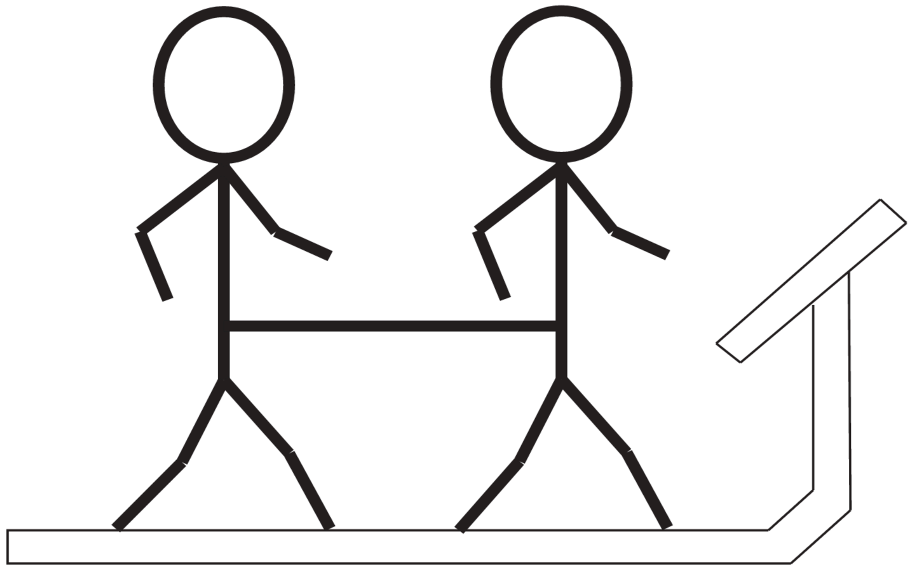

Figure 2. Simulating a quadruped with two mechanically coupled humans

This simulation of a quadruped with mechanically coupled humans may superficially seem like a very strange arrangement at first but it provides the possibility of exploring research questions with a wide range of applications. The first advantage of the set-up is that it provides a very quick, simple, and inexpensive way to study the energetic effects of various stepping patterns, as mentioned before. Quantifying these effects and determining the energy optimal gait may have important applications in the field of quadruped robotics. Quadruped robots are becoming more and more popular as they offer a better alternative to traversing rough terrain (Kiguchi et al., 2002). Energy optimal gaits determined through this study can perhaps be applied to quadruped robots in order to reduce their total energy consumption. Any decrease in total energy used allows for longer battery life and a more efficient overall robot. Along with exploring stepping patterns, this unique mechanically coupled human scenario will also provide another study under the energy optimization hypothesis. After knowing which gaits are energetically optimal, the mechanically coupled humans can be naturally observed and see which gait they prefer. The results from this study have a wide range of applications that all stem from the specific objectives of the study.

Section 1.3 Objectives

The background and motivation from previous research, presented above, led to several distinct objectives for this study. The objectives of this study are to:

- Determine the preferred stepping pattern for this mechanically coupled human locomotion
- Measure the energetic effect caused by mechanically coupling the humans together
- Quantify the relationship between stepping pattern and energy consumption

The study was designed in order to accomplish these three main objectives so as to test the energy optimization hypothesis. The following sections present the methodology used to test for these objectives along with the results and outcomes of the study.

Chapter 2: Methodology

Section 2.1 Defining stepping pattern

Consider two humans walking, one in front of the other, simulating a quadruped. We assume for simplicity that the motions of the four legs of this quadruped are identical except for phase differences between their motions. Here, we defined the **stepping pattern** as the relative phase of the quadruped's back left leg with respect to the front left leg of the quadruped. Five different stepping patterns were analyzed throughout the trials of this experiment: In-Sync (0° phase shift), 45° phase shift, 90° phase shift, 135° phase shift, and Out-of-Sync (180° phase shift). The five stepping patterns relate the back left foot's time of contact with the ground to the front left foot's time of contact with the ground. These stepping patterns are illustrated in Figures 3-7. A shaded box represents the time period of the foot's contact time with the ground, and for simplicity, we have depicted normal human walking without a double stance phase.

Legend for Figures 3-7: F – Front, B – Back, L – Left, R - Right

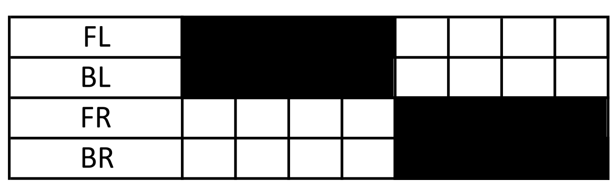

Figure 3. In-Sync (0° phase shift) stepping pattern

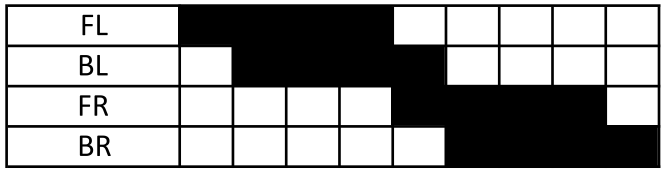

Figure 4. 45° phase shift stepping pattern

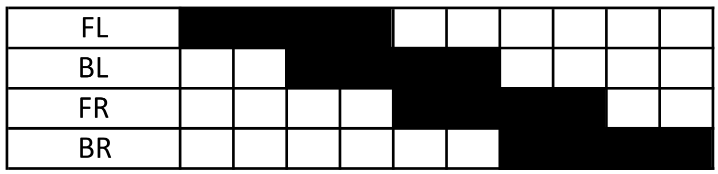

Figure 5. 90° phase shift stepping pattern

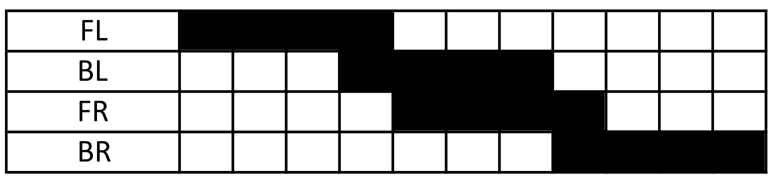

Figure 6. 135° phase shift stepping pattern

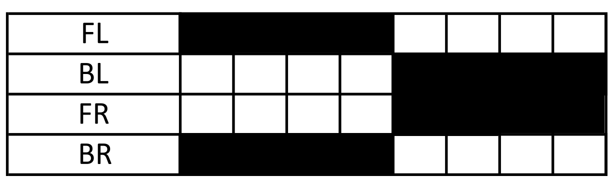

Figure 7. Out-of-Sync (180° phase shift) stepping pattern

In Figures 3-7, each foot has the same contact time with the ground, four frames ("boxes") long. In Figure 3, In-Sync walking is shown as the front left foot and back left foot are making contact with the ground at the same exact time. In Figure 4, the back left foot is now slightly delayed (45° phase shift) and makes contact with the ground 1 frame behind the front left leg. A 90° phase shift, shown in Figure 5, has the back left foot making contact with the ground two frames after the front left foot does. Figure 6, depicts a 135° phase shift in which the back left foot makes contact with the ground three frames after the front left leg and in Figure 7 the back left leg now lags an entire step behind to where the front left leg is making contact with the ground at the same time as the back right leg, Out-of-Sync walking (180° phase shift).

Section 2.2 Controlling and analyzing stepping pattern

We now describe how we made the subjects walk in each of the different stepping patterns for the trials. Feasibility trials indicated that visual cues or simple verbal instructions were not effective. The best solution to this problem was to provide the subjects with audible cues to listen to during the trial. This way the subjects could simply sync their steps to an audio beat and they would walk in the various stepping patterns. A very simple beep sound file was created using MATLAB. This file was simply a four minute long audio recording of a series of beeps. The timing of the beats were based on the measured average step time of several subjects along with the fixed speed chosen for the treadmill for the trials. In order to introduce the phase shifts, three additional sound files were created with a slight time shift at the beginning of the audio file. In the trials, the front subject would always listen to the same base audio file with no time shift. The back subject would listen to the files with the varying time shifts in order to induce the different stepping patterns. Each subject had their own audio playback device and wore headphones during the trials. At the beginning of each trial, I would start both of the audio files at the same time and then hand the devices to the subjects, instructing them to focus only on walking to the beat of the sound. One potential source of error with this way of controlling stepping pattern is when the researcher starts the audio files at the same time. In order to make sure this did not affect the results of the study, we later confirmed the stepping pattern of the subjects using the collected data.

During the trials, ground reaction forces from the legs of the subjects were collected using force sensors installed in the treadmill. These ground reaction forces were used to determine exactly which stepping pattern the subjects were walking in at all times. From the graph of the force component acting in the z direction (vertical), specific trends can be seen for normal individual walking.

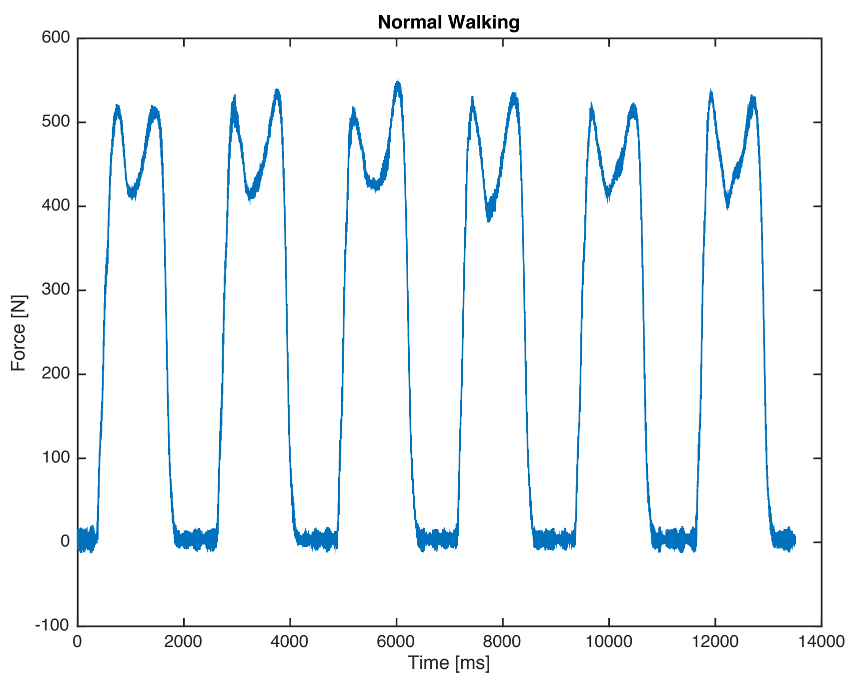

Figure 8. Observed pattern for individual walking

In order to accurately determine which stepping pattern the subjects were in, the ground reaction force shape, shown in Figure 8 for an individual person walking, needed to be determined for each of the different stepping patterns to be used. With four legs walking on the treadmill, each belt of the treadmill was measuring forces from two legs and combining them into one force, which we were recording as the ground reaction force. We assume that the ground reaction force which we were measuring was a combination of the front legs walking normally and the back legs walking with a phase shift of either 45°, 90°, 135°, or 180° (we assume that the coupling does not substantially change the individual ground reaction force profile). The ground reaction force in the z direction for both the front and back legs can be seen in Figure 9 below. The blue line represents normal walking of the front legs while the orange line shows a 45° phase shifted stepping pattern.

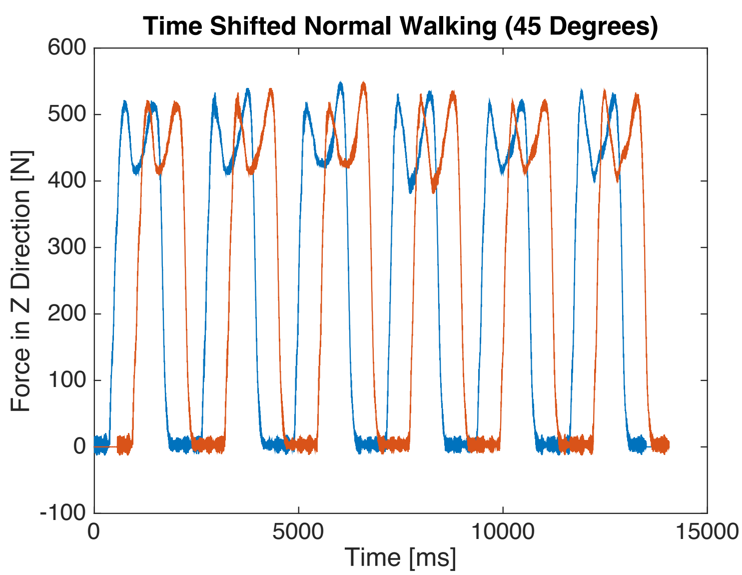

Figure 9. Time shifted normal walking (45°)

This time shifting of the normal walking was completed for each of the different phase shifts. In order to predict what the different stepping patterns would look like, the two shapes, seen in Figure 9, were added together for each of the stepping patterns. This addition of the two shapes provided us with the approximate shapes we would expect to see in the z direction ground reaction forces for each stepping pattern. The results are shown in Figures 10 and 11 on the pages below. Note that the shape for In-Sync and Out-of-Sync walking are not shown because they are identical to the shape for the individual walking as both legs are striking the ground at the same time in the In-Sync case and only one leg on each side of the treadmill is moving at a time for Out-of-Sync walking. The 135° phase shift is not depicted because it is identical to the image for the 45° phase shift. With these predicted shapes, we could determine what stepping pattern the subjects were walking in at every instance in time. This was used to analyze the data collected from the final experimental trials.

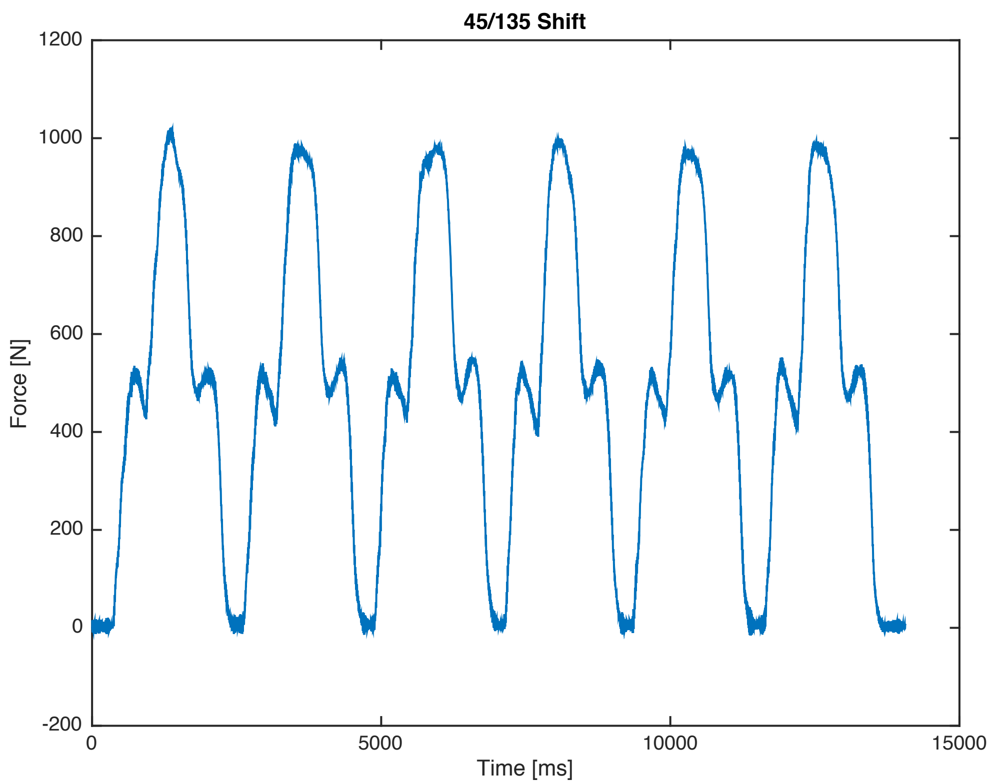

Figure 10. Predicted pattern for 45° and 135° phase shift walking

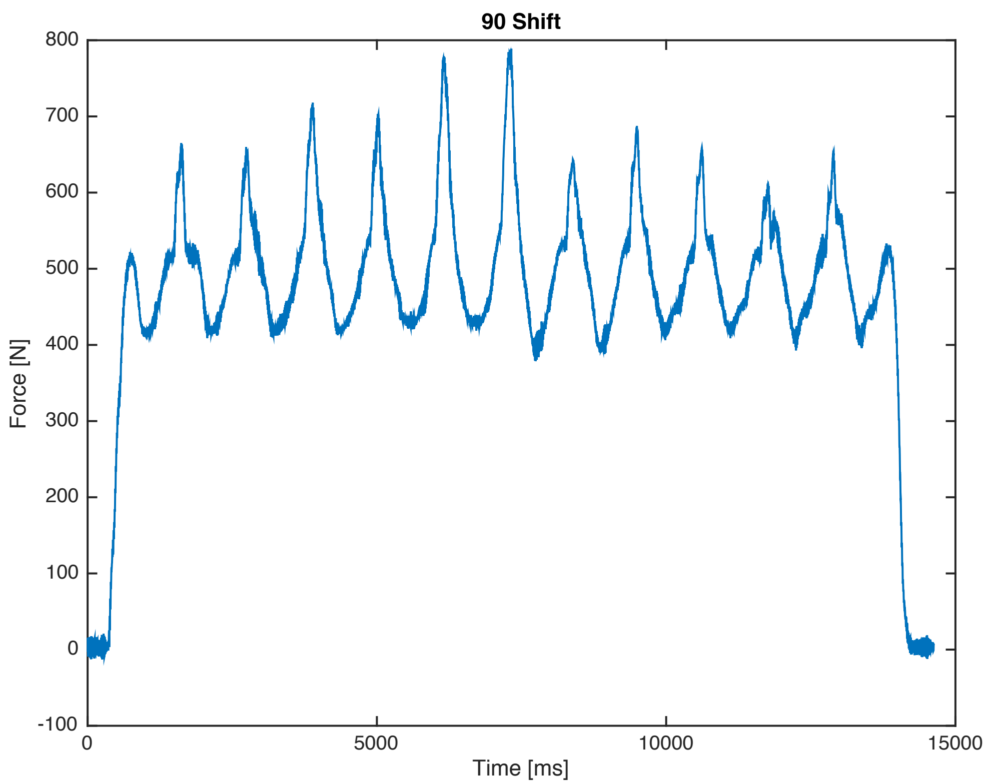

Figure 11. Predicted pattern for 90° phase shift walking

Section 2.3 Mechanical coupling device

For the purpose of this study, a quadruped subject was needed to enable walking in the different stepping patterns. Two humans were mechanically coupled together in order to simulate the quadruped. At first a rigid wooden bar was used to couple the subjects together. Each subject wore a gait belt around their waist and the wooden bar was attached between them. Through several feasibility trials the wooden bar proved to be a problem. The subjects could not naturally walk and were having trouble walking in the different stepping patterns. In attempt to make a model closer to a quadruped animal with a bit of compliance in the "spine" or coupling, a hula-hoop was used to couple the subjects, replacing the previous rigid wooden bar. The hula-hoop still provided a sturdy structure for connecting the two humans but also provided some flexibility allowing a more natural walking movement for the subjects. The subjects were able to maintain the stepping patterns much more efficiently in the new setup. The hula-hoop provided a stiffness to the coupling as well.

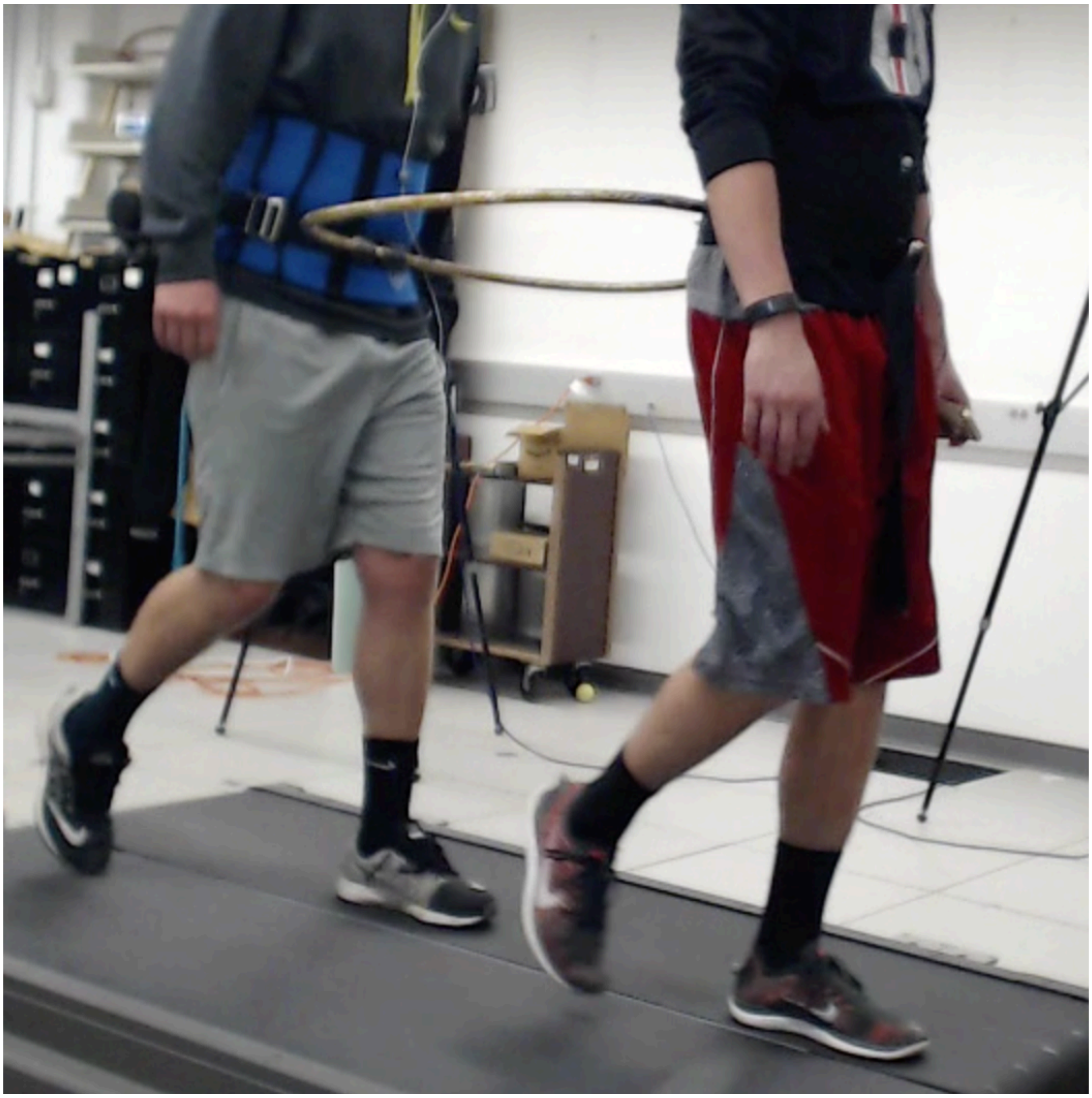

Figure 12. Mechanically coupling two humans to simulate a quadruped

Section 2.4 Experimental procedures

All of the trials for this experiment were conducted on the treadmill depicted in Figure 13. The treadmill is comprised of two different belts with force sensors underneath each of the belts. Motion capturing cameras were set up in a circle all the way around the treadmill. Subjects had reflective markers attached to them in four different spots in order to collect motion data from the cameras. Each subject had a marker on both heels, near the navel and directly behind the navel (near the sacrum) on the back. The heel markers were used to track position of the feet while the navel markers tracked the velocity of the center of mass.

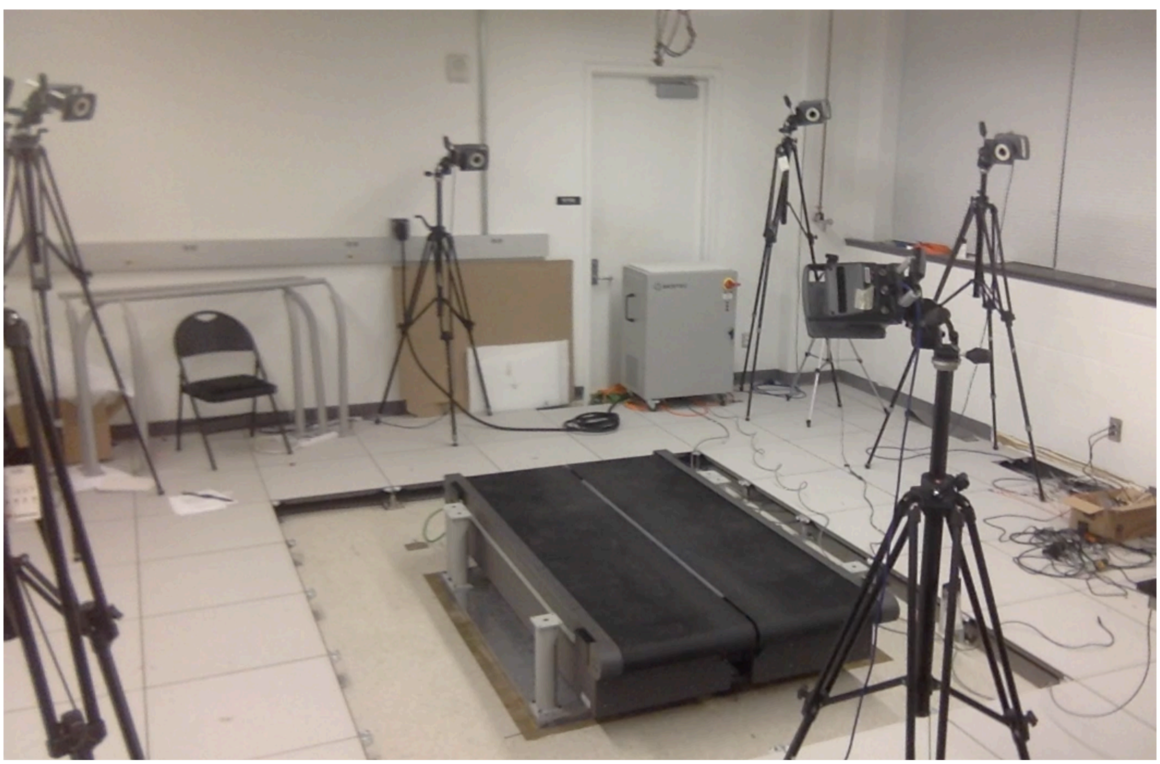

Figure 13. Treadmill and motion capture cameras

In every experiment, each subject walked in a total of six different trials on the treadmill. This is summarized in Table 1 below. All trials were conducted at a fixed speed of 1.2 meters per second, a speed selected to be just below normal preferred human walking speed. The speed was picked slightly below preferred walking speed for safety concerns in this novel coupled scenario. Each of the trials lasted for approximately two minutes. Before each trial began, I selected the appropriate audio files and played them through the audio device for each subject. The treadmill was then started and allowed to come to steady state. Data was then collected for thirty seconds after the subjects had walked for about 1.5 minutes. This process was repeated for each of the different trials shown below. The entire experimental procedure was completed with four different pairs of subjects.

Table 1. Experimental trials conducted

Trial	Stepping Pattern
1	Individual Walking Subject 1
2	Individual Walking Subject 2
3	Coupled In-Sync Walking
4	Coupled 45° Phase Shift Walking
5	Coupled 90° Phase Shift Walking
6	Coupled 135° Phase Shift Walking
7	Coupled Out-of-Sync Walking

The ground reaction forces were the main measurements taken from the trials. These measurements were used to calculate both the center of mass velocity and eventually the estimated metabolic rate. The next section explains the data analysis performed on the ground reaction forces measured during the experimental trials.

Section 2.5 Participant details

All subjects that participated in this trial did so after providing informed consent and The Ohio State University's Institutional Review Board approved all of the protocols for this study. Subjects volunteered for the experiment with the requirement that they were healthy enough to complete all of the required walking tasks for the study. All subjects, except for one older male, were between the age of 20 and 23 years old. A total of eight subjects took part in feasibility trials while another eight subjects took part in the final experimental trials. There were approximately 10 different males subjects and 2 female subjects. The males had an average height of 5'11" with an average weight of 182 lbs. The female subjects had an average height of 5'3" and an average weight of 142 lbs. Subjects were paired together based on several physical quantities, height, leg length, and weight. These quantities were important to control in order to simulate a quadruped, such as a horse, as closely as possible. A similar height in the front and back was desired along with a close balance of weight as well. Leg lengths were matched in attempt to make all four legs as similar as possible.

Section 2.6 Estimating metabolic rate

One of the main objectives of the study was to determine the relationship between stepping pattern and estimated metabolic rate. After completing the trials, the ground reaction forces along with the time at which each force occurred were both known. I estimated the metabolic rate from these values. Margaria (1968) measured the efficiency of muscle's energy expenditure for both positive and negative work. These muscle efficiencies are reflected in the constants in Equation 1, relating the estimated metabolic rate to both the net positive mechanical power and net negative mechanical power (Margaria, 1968; Srinivasan, 2006).

$$\dot{E} = 4[P_1]^{+} + .83[P_1]^{-} + 4[P_2]^{+} + .83[P_2]^{-}$$

Equation 1

$$P_1 and\ P_2 - Net\ Mechanical\ Power\ [W]$$

$$\dot{E} - Estimated\ Metabolic\ Rate\ [W]$$

Muscles use four times as much energy as the work being performed for positive work (25% efficiency, hence the factor of 4 in Equation 1) while during negative work the work performed is actually 1.2 times greater than the energy expenditure of the muscles (Margaria, 1968). In order to use this derived equation, the net mechanical power for the subject's legs needed to be calculated. Using Equations 2 and 3, we approximated the net mechanical power for the ground reaction forces from each of the treadmill belts.

$$P_1 = F_{gr} \bullet V_{com}$$

$$P_2 = F_{gl} \bullet V_{com}$$

Equations 2 and 3

$$P_1 \, and \, P_2 - Net\ Mechanical\ Power\ of\ right\ and\ left\ legs\ [W]$$

$$F_{gr}\ and\ F_{gl} - Ground\ Reaction\ Forces\ on\ right\ and\ left\ belts\ [N]$$

$$V_{com} - Velocity\ [m/s]$$

There is one more piece of information needed to perform the calculations above: the center of mass velocity for the two subjects. In order to calculate this velocity, Equations 4 and 5 shown on the next page were utilized. With both ground reaction forces and the combined mass of the subjects known, Newton's second law was used to calculate the acceleration of the center of mass for the two subjects (Equation 4). Then, by integrating the accelerations from the initial center of mass velocity, we found the velocity of the center of mass as a function of time (Equation 5). To avoid drift in the velocity estimates, we subtracted a constant of the velocity estimates so that the mean sideways and vertical velocity are zero and the mean fore-aft velocity was the treadmill belt velocity.

$$F = ma$$

Equation 4

$F - Force\ [N]$

$m - Mass\ [kg]$

$a - Acceleration\ [m/s^2]$

$$V_{com}(t) = v_o + \int_0^t a\,dt$$

Equation 5

$V_{com} - Velocity\ [m/s]$

$v_o - Initial\ Velocity\ [m/s]$

$a - Acceleration\ [m/s^2]$

Section 2.7 Extracting Time Periods for Individual Stepping Patterns

In order to calculate the estimated metabolic rate for each stepping pattern using equations developed in the previous sub-section, we had to identify and extract the periods in which the subjects used the different stepping patterns using the ground reaction force data. The stepping pattern shapes presented earlier in Figures 8, 10 and 11 predict what the different stepping patterns will look like in the ground reaction forces (z direction) data. Using visual inspection of the ground reaction force data, I determined which particular stepping pattern (relative leg-phasing) the subjects were walking in. Even though the subjects made an effort to control their stepping pattern, they seemed to drift between the stepping patterns in several of the trials. First, I extracted the different time frames during which the subjects obeyed the prescribed stepping pattern, and only this data was used to compute the metabolic rate. Second, I determined the total percentage of time that the subjects spent walking in each of the stepping patterns. This information provides key insight into the preferred stepping pattern for the subjects in this mechanically coupled situation. The results determined from all of the data analysis are summarized in the following sections.

Chapter 3: Results and Discussion

Section 3.1 Estimated metabolic rate results

Estimated metabolic rate calculations were performed for each of the different stepping patterns for all four sets of tested subjects. The results were compiled and organized into Figure 14 below as a box plot.

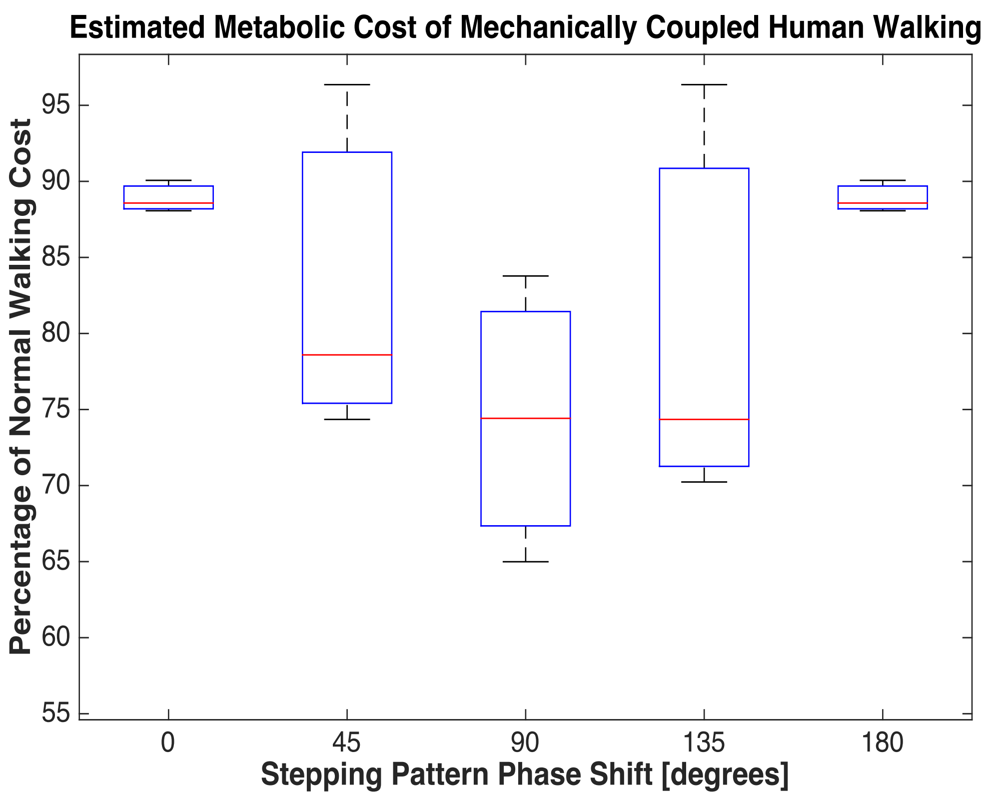

Figure 14. Estimated metabolic cost of mechanically coupled human walking, pooled over four subject pairs

The red line seen for each data set represents the median value for that stepping pattern, the blue box represents the 25^{th} to 75^{th} percentile of the data set, and the two black dashed lines that form the very end of each box plot correspond to the minimum and maximum values for the values of that stepping pattern.

In Figure 14, the estimated metabolic rates in various conditions are normalized based on the subjects combined individual walking energy consumption. This was used as a comparison for how the coupling device was affecting the total energy consumption of the individuals. The total estimated energy consumption by the subjects is seen to have decreased for every different stepping pattern. This suggests that the coupling device is actually helping the subjects to walk in some manner. This is an interesting phenomenon of this coupled scenario that could lead to future research. Figure 14 suggests that a 90° phase shifted stepping pattern appears to be the most energy optimal solution. This could, however, be due to limitations of the estimated metabolic rate calculation that will be discussed in the following section. The variability of the data for the intermediate phases (45°, 90°, 135°) could also be due to the limitations of the calculation.

Section 3.2 Limitations of the calculation to estimate metabolic rate

Donelan, Kram, and Kuo (2002) explored the affects of calculating mechanical work while positive and negative work were occurring at the same time. Their hypothesis was that when multiple acting forces were being combined into a single acting force, an external work calculation would show decreased mechanical work due to the cancellation of the positive and negative work occurring at the same time (Donelan et al., 2002). The researchers concluded that the "combined limbs method" calculations were around 33% lower than their other method using the reaction forces from each individual leg. The combined limbs scenario directly applies to the calculation for my study. On each treadmill belt there are two forces acting at the same time that are being combined into a single force. In the stepping patterns where different kinds of work are being performed at the same time (mainly the intermediate phases), the calculated metabolic rates are lower than the actual metabolic rates of the subjects. The In-Sync walking calculated values would not be affected however because the legs are performing the same kind of work at the exact same time. Out-of-Sync walking calculations would only slightly be affected by this limitation because there are only a few time frames where two legs are performing different types of work on one of the belts at the same time. The intermediate phases, where two legs are performing different work simultaneously for most of the time, would see the largest difference between calculated metabolic rates and actual metabolic rates. In particular, our calculations would underestimate the metabolic cost based on mechanical work for the intermediate phases, thus artificially lowering the estimates.

Section 3.3 Time spent in each stepping pattern results

In previous studies, researchers showed that animals and humans naturally spend most of their time walking in some energy optimal gait based on their situation (Hoyt and Taylor, 1981; Handford and Srinivasan, 2014). Motivated by such evidence, I determined the percentage of time the subjects spent in each of the stepping patterns and the one with the highest percentage is their preferred stepping pattern, or energy optimal stepping pattern, for this particular mechanically coupled situation. As discussed earlier in Section 2.6, I compared the collected ground reaction force data with the predicted stepping pattern shapes to determine for each section of data which stepping pattern the subjects were walking in. Adding the total time spent for each set of subjects in each of the stepping patterns and dividing by the total time of the trials, I determined the percentage of time spent in each of the different stepping patterns. The results are shown below in Figure 15.

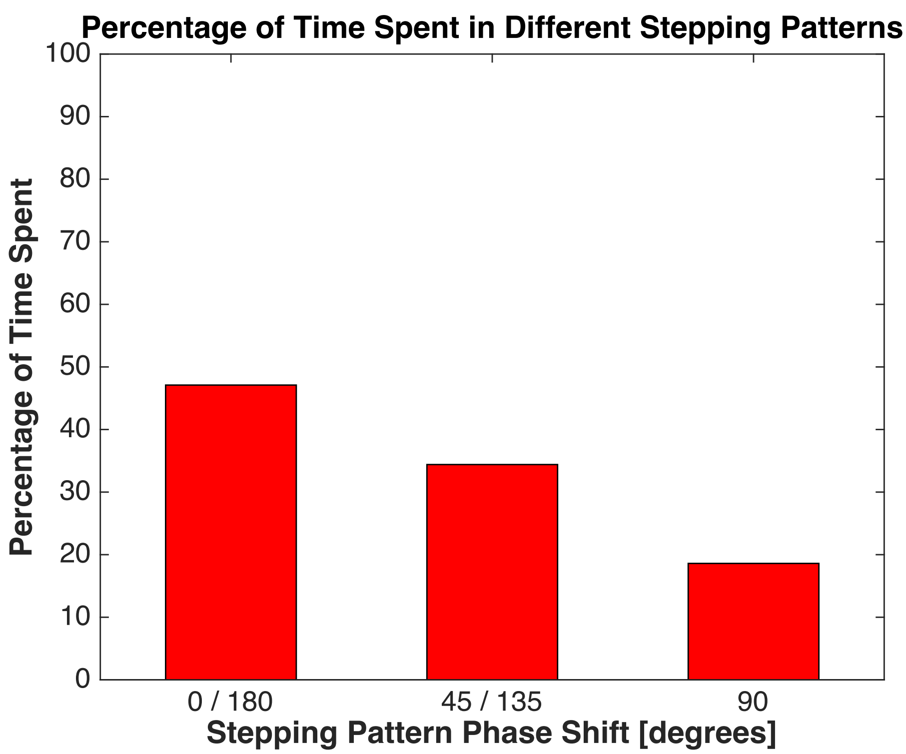

Figure 15. Percentage of time spent in each stepping pattern in the specific trials where the subjects were instructed to walk in those stepping patterns

Figure 15 shows that the subjects spent the most time walking In-Sync or Out-of-Sync. Based on visual inspection during the trials, along with watching the recorded trials afterwards, it can be seen that the majority of this time is actually In-Sync walking. Even though I was trying to control the stepping patterns through the use of audio cues, the subjects continually drifted back to In-Sync walking. This is evidence that In-Sync is the more preferred stepping pattern for this mechanically coupled situation and is perhaps the energy optimal gait as well, at least for the mechanical coupling that we explored.

Chapter 4: Conclusions and Future Work

Section 4.1 Conclusions of the study

We have somewhat conflicting results between the stepping pattern preferred by the subjects and the energy optimal stepping pattern as determined by the mechanical work calculations for this mechanically coupled scenario. Specifically, the estimated metabolic rate calculations show a 90° phase shift stepping pattern being energy optimal while the actual preferred stepping pattern based on total time spent is In-Sync walking (0° phase shift). However, as previously noted, our net work based metabolic cost likely underestimates the metabolic rate for the intermediate 90° phase shift – it is possible that when computed without this underestimation, that the 90° phase shift is still the optimum stepping pattern, or that the 90° phase shift has the greatest energy cost. Increasing the intermediate phase metabolic rates by approximately 33% (Donelan et al., 2002), In-Sync walking now becomes the energy optimal gait for the calculations as well. Due to the cost under-estimations, it may be that the energy optimal and preferred stepping pattern for this mechanically coupled scenario is In-Sync walking. This conclusion can also be further explored through a more accurate measure of the energy consumption in this scenario.

Section 4.2 Future work

There are other methods for measuring the energy consumption or metabolic rate of human subjects other than the external work calculation used in this study. An indirect calorimetric measurement of the total oxygen consumption (VO2 measurement) provides a much more accurate method for the actual metabolic rate of the human or animal being measured. This technique was not used in this trial due to several time constraints. First, the individual trials for a VO2 measurement must be longer in order to get a good reading. Second, each experiment must have been completed twice for each set of subjects in order for each subject in the coupling to wear the oxygen mask (the device can only measure oxygen consumption for one subject at a time and we had access to only one device). Due to these restrictions, the VO2 measurement was not used in this study. However, it is part of our future plan to measure the exact metabolic rate related to each stepping pattern. One thing to consider for future studies is how to better control the subject's stepping pattern. Although audio cues worked well enough for the purpose of this study, for studies using a VO2 measurement the subjects will have to remain in specific stepping patterns for much longer periods of time. Additional feasibility studies will be needed to test new methods of controlling stepping pattern. Another option for better controlling stepping patterns is training the subjects for extended periods of time before the trials or using subjects with previous syncing experience such as dancers or marching band members. Other future work or studies will involve different levels of coupling and performing an analogous study on a quadruped robot.

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